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EXECUTIVE SUMMARY

AEROSOL DEPOSITION PARAMETERS

G.L. Ogram  
Research Scientist  
Atmospheric Research Section

Methods are recommended for estimating deposition velocities and washout coefficients for aerosols of 0.2 to 10 micron diameter. These methods reflect the current understanding of aerosol deposition processes, are capable of describing the dependence of deposition rates on such important factors as wind speed, particle size and surface aerodynamic roughness, and have been adapted here to ensure that they are reasonably straightforward in application and provide values representative of Ontario Hydro's NGS sites. Potential uncertainties in predicted deposition parameters are also estimated.



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|-----|----------------|------|--------|------|-----------------|------------|----------|
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Mr. H.N. Isaac  
Manager, Nuclear Materials  
Design and Dev - Gen



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Methods are recommended for estimating deposition velocities and washout coefficients for aerosols of 0.2 to 10 micron diameter. These methods reflect the current understanding of aerosol deposition processes, are capable of describing the dependence of deposition rates on such important factors as wind speed, particle size and surface aerodynamic roughness, and have been adapted here to ensure that they are reasonably straightforward in application and provide values representative of Ontario Hydro's NGS sites. Potential uncertainties in predicted deposition parameters are also estimated.

#### 1.0 INTRODUCTION

The Nuclear Materials Management Department (NMMD) requested assistance in selecting suitable aerosol (or particulate) deposition velocities and washout coefficients for use in the Ground Contamination Study. These parameters were to be provided "in the form of best estimates with reasonable uncertainty bounds"/1/.

Two different release characteristics were to be considered:

- a) "a short duration (15 minutes) release of liquid aerosols in the range of 1 to 10 micron diameter, density  $1.0 \text{ g cm}^{-3}$ ; and,
- b) a long duration (weeks) release of solid and hygroscopic aerosols in the range 0.2 to 1 micron diameter, density from  $1.0$  (larger size) to  $6.2 \text{ g cm}^{-3}$  (smaller size). The size distribution is....strongly peaked, where the peak number density could be within the range 0.2 to 1.0 micron"/1/.

Deposition parameters were to be supplied as a function of wind velocity, (Pasquill-Gifford-Turner atmospheric) stability category and rain intensity.

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Recent literature on the subject was surveyed and suitable methods selected for determining dry deposition velocity and washout ratio. The deposition of particles in the 0.1 to 1 micron diameter range is particularly difficult to treat as the dominant aerosol transport mechanisms of Brownian diffusion and gravitational settling are not effective in this size range. Particles  $> 1$  micron tend to be transported by settling, whereas particles  $< 0.1$  micron are transported efficiently by Brownian diffusion.

The recommended dry and wet deposition models are discussed in Sections 2 and 3 respectively. An attempt was made to select models that:

- a) have been published in the refereed literature;
- b) can be readily generalised to deal with the effect of factors known to be of importance in controlling deposition rates;
- c) provide a physically reasonable dependence of deposition parameters on the above factors; and
- d) give reasonable agreement with available experimental data.

Sections 2.1 and 3.1 explain how to determine dry deposition velocities and washout coefficients. Uncertainty ranges were estimated by comparing predicted parameters with experimentally measured values and are given in Section 2.2 and 3.2.

## 2.0 DRY DEPOSITION MODEL

The deposition velocity is usually used to model the deposition of material from the atmosphere to terrestrial surfaces. It is defined as the ratio of the downward flux to the concentration at a certain reference height above the surface (usually 1 m). The model put forward by Sehmel and Hodgson/2,3,4,5/ was selected here as a basis for providing aerosol deposition velocities as it provides a good combination of comprehensiveness and physical realism. It is recommended by Sehmel in his recent review of dry deposition in the document "Atmospheric Sciences and Power Production"/5/ where he states that he considers the model "to so improve our capability to predict deposition velocities that it should be used until either more refined and definitive deposition experiments are completed or improved predictive models are developed from existing data".

Sehmel's model expresses deposition velocity,  $V_g$ , in terms of the friction velocity,  $u_*$ , (which can be related to wind speed,

$u$ ), particle diameter,  $d$ , surface roughness length,  $z_0$ , aerosol density,  $\rho$ , and atmospheric stability (through the Monin-Obukhov length,  $L$ ).  $V_g$  can vary greatly with these parameters for  $d$  between 0.1 and 10 microns (sometimes by orders of magnitude).

$V_g$  is given by the following expression

$$V_g = \frac{V_t}{[1 - \exp(V_t \text{Int}/u_*)]} \quad (1)$$

which for  $V_t \ll V_g$  becomes

$$V_g = u_* / \text{Int} \quad (2)$$

where the aerosol settling velocity is/6/

$$V_t = \frac{\rho d^2 g}{18\mu} \quad (3)$$

( $\mu$  is the viscosity of air and  $g$  is gravitational acceleration) and  $\text{Int}$  is a resistance integral given as the sum of two terms;  $\text{Int}_3$ , which describes the resistance to deposition from a distance of 1 cm above the surface (due to such factors as diffusional resistance, just above and within the deposition surface canopy, and the interaction of the aerosol with the deposition surface), and  $\text{Int}_{1-2}$  which describes the resistance to atmospheric transport from the reference height for concentration (1 m above the surface) to a height of 1 cm above the surface, ie

$$\text{Int} = \text{Int}_3 + \text{Int}_{1-2} \quad (5)$$

Sehmel derived the following semi-empirical correlation for  $\text{Int}_3$  from carefully controlled wind tunnel studies of the deposition of mono-disperse particles to surfaces of various roughness.

$$\begin{aligned} \text{Int}_3 = & - \exp \left\{ -378.051 + 16.498 \ln(\text{Sc}) \right. \\ & + \left[ \ln \tau^+ \right] \left[ -11.8178 - 0.28628 \ln \tau^+ \right. \\ & \left. \left. + 0.32262 \ln\left(\frac{d}{z_0}\right) - 0.33850 \ln\left(\frac{D}{z_0 u_*}\right) \right] - 12.8044 \ln d \right\}. \end{aligned} \quad (6)$$

$D$  is the Brownian diffusion coefficient of the aerosol/3/

$$D = \frac{kT}{3\pi\mu d} \left\{ 1 + \frac{2 \times 10^{-4}}{Pd} [6.32 + 2.01 \exp(-1095 P d)] \right\} \quad (7)$$

where P is pressure (cm Hg) and T is temperature (K).

Sc is the aerosol Schmidt number, ( $Sc = \nu/d$  where  $\nu$  is the kinematic viscosity of air)

$\tau^+$  is a non-dimensional relaxation time given by

$$= \frac{\rho d^2 u_*^2 \times 10^{-8}}{18 \mu \nu} \quad (8)$$

The following simplifications are suggested in order to calculate values of  $V_g$  for the present purpose. The approximations listed below reduce  $V_g$  to a function of two variables, aerosol diameter and wind speed.

- Take  $Z_0 = \text{const} = 10 \text{ cm}$ . This choice of  $Z_0$  is a reasonable spatial average for the terrain surrounding Hydro's NGS facilities (see Table 1) and is the default value suggested in the Province of Ontario's draft emergency response procedures/8/.
- Assume particle density,  $\rho = \text{const} = 1 \text{ g cm}^{-3}$ .  $V_g$  is independent of  $\rho$  for  $0.2 < d < 1 \text{ micron}$  and is specified as  $1 \text{ g cm}^{-3}$  for  $d > 1 \text{ micron}$ .
- Approximate Intl-2 by using the expression for resistance to momentum transfer in a neutral atmosphere/3/, ie

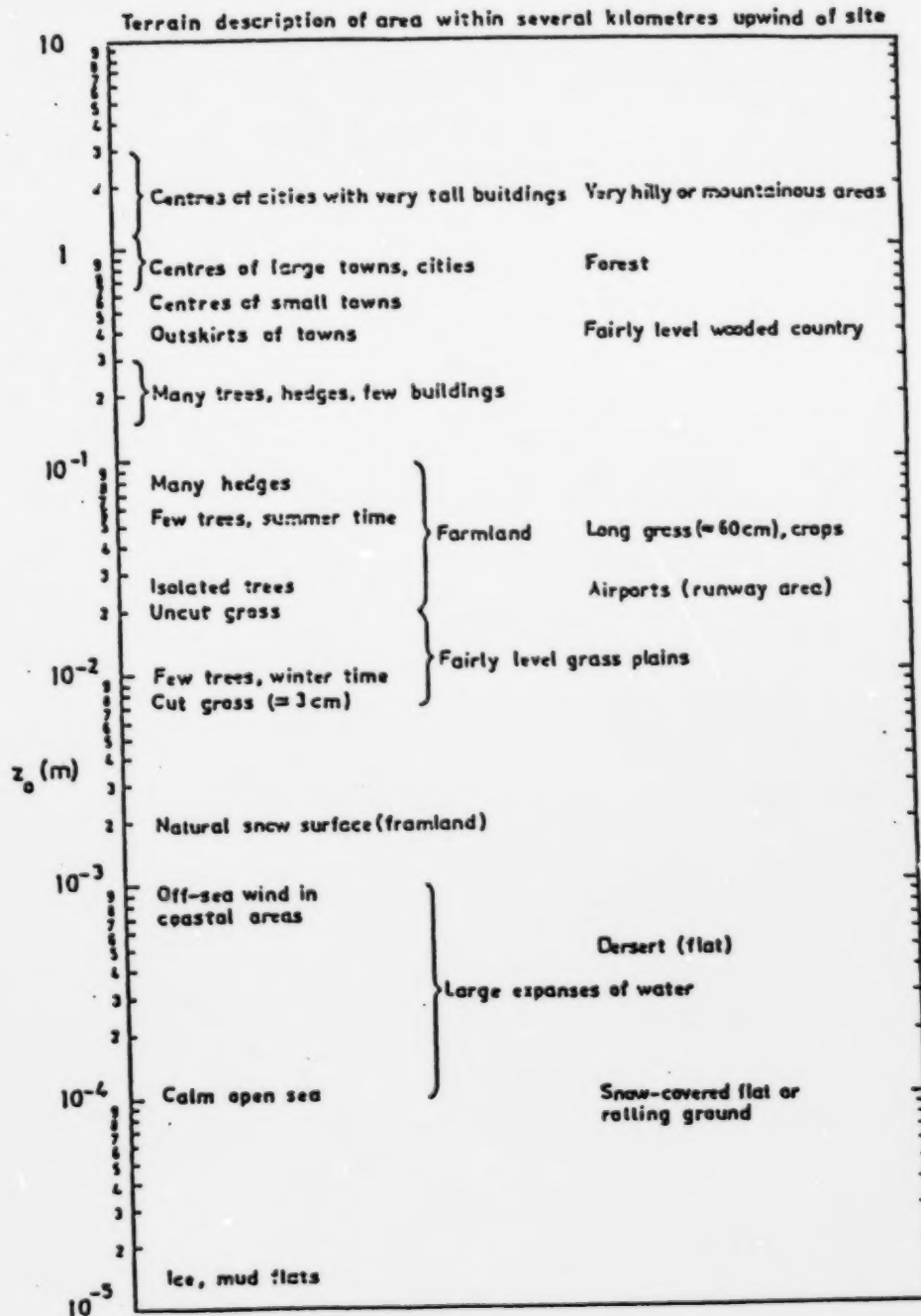
$$\text{Intl-2} = \int_{Z=100\text{cm}}^{Z=1\text{cm}} [0.35 (Z + Z_0)^{-1}] dz = [2.86 \ln [Z+Z_0]]_{Z=100\text{ cm}}^{Z=1\text{cm}}$$

For  $Z_0 = 10 \text{ cm}$ ,  $\text{Intl-2} = -6.6$ . As shown by Sehmel/2,3/, for concentrations referenced to a 1 m height, the effect of stability on Int, and hence predicted  $V_g$ 's through Intl-2, is small as (1) the contribution of Intl-2 to Int usually dominates and (2) the effect of stability (ie L) on the magnitude of Intl-2 is relatively small. Physically, the latter reflects the fact that mechanically generated turbulence tends to dominate in the first meter of the atmosphere giving locally "near neutral" conditions. Note

Table 1

(after Hanna et al /7/)

$z_0$  values for typical terrain types



too, that stability is treated within Sehmel's model through (the precisely defined concept of)  $L$ , which cannot be unambiguously related to (the relatively ill-defined concept of) PGT stability class. For these reasons, it is suggested that the dependence of  $V_g$  on stability be ignored when using these  $V_g$ 's with dispersion models using the PGT stability classifications. Note that the effect of atmospheric stability can be easily accounted for if  $L$  is available.

- Relate  $u^*$  to the wind speed,  $u$ , by the power law profile for a near neutral atmosphere/9,10/, ie

$$u/u^* = 2.86 \ln [Z + Z_0] / Z_0$$

which gives  $u/u^* \sim 13$  for  $u$  measured at the standard 10 m height,  $u$  (10m)<sup>\*</sup> and  $Z_0 = 10$  cm. As with the resistance to atmospheric transfer, this ratio depends on stability through  $L$  but the effect on inferred  $V_g$ 's is relatively small (see Appendix A).

- The growth of hygroscopic particles in the region of enhanced relative humidity near the surface has been ignored. Available evidence appears to indicate that particle residence times in this region are usually insufficient for more than a factor of two increase in  $V_g$  for sub-micron particles/11/.

Table 2 shows values of  $V_g$  calculated using (1), (2) and (3), with the above assumptions, for various wind speeds and particle diameters. Results are also plotted in Figure 1. Calculated  $V_g$ 's show a distinct minimum at about  $d = 0.3 \mu m$  and increase significantly with wind speed.

## 2.1 Recommended Deposition Velocities

### 2.1.1 Particle Diameter 0.2 to 1 Micron Narrow Size Distribution

$V_g$ 's may be read from Table 2 or from Figure 1 for the appropriate wind speed and particle size. (Interpolation may be used for intermediate wind speeds).

Alternatively,  $V_g$ 's can be calculated as a function of  $u$  and  $d$  using equation (1), ie

$$V_g = V_t / \{1 - \exp (V_t \text{Int}/u^*)\} \quad (9)$$

Table 2

PARTICLE DEPOSITION VELOCITIES (cm/s) FOR VARIOUS WIND SPEEDS  
AND PARTICLE DIAMETERS (NEUTRAL ATMOSPHERE INT1-2 = -6.6)

ROUGHNESS LENGTH Z<sub>0</sub> = 10 cm  
PARTICLE DENSITY = 1 g/cm<sup>3</sup>

| DIAM (μm) | WIND SPEED u (m/s) |         |         |         |         |
|-----------|--------------------|---------|---------|---------|---------|
|           | 2.0                | 5.0     | 10.0    | 15.0    | 20.0    |
| 1.0E-01   | 8.8E-02            | 9.1E-02 | 1.6E-01 | 2.6E-01 | 4.1E-01 |
| 2.0E-01   | 4.9E-02            | 4.6E-02 | 7.3E-02 | 1.2E-01 | 1.8E-01 |
| 3.0E-01   | 4.5E-02            | 4.2E-02 | 6.7E-02 | 1.1E-01 | 1.7E-01 |
| 4.0E-01   | 4.9E-02            | 4.7E-02 | 7.5E-02 | 1.2E-01 | 1.9E-01 |
| 5.0E-01   | 5.6E-02            | 5.4E-02 | 8.9E-02 | 1.5E-01 | 2.3E-01 |
| 6.0E-01   | 6.5E-02            | 6.5E-02 | 1.1E-01 | 1.8E-01 | 2.8E-01 |
| 7.0E-01   | 7.5E-02            | 7.6E-02 | 1.3E-01 | 2.2E-01 | 3.4E-01 |
| 8.0E-01   | 8.6E-02            | 9.0E-02 | 1.5E-01 | 2.6E-01 | 4.1E-01 |
| 9.0E-01   | 9.8E-02            | 1.0E-01 | 1.8E-01 | 3.1E-01 | 4.9E-01 |
| 1.0E+00   | 1.1E-01            | 1.2E-01 | 2.1E-01 | 3.6E-01 | 5.8E-01 |
| 2.0E+00   | 2.7E-01            | 3.5E-01 | 6.8E-01 | 1.2E+00 | 2.0E+00 |
| 3.0E+00   | 4.6E-01            | 6.7E-01 | 1.4E+00 | 2.5E+00 | 4.2E+00 |
| 4.0E+00   | 6.5E-01            | 1.0E+00 | 2.2E+00 | 4.1E+00 | 6.7E+00 |
| 5.0E+00   | 8.3E-01            | 1.4E+00 | 3.1E+00 | 5.7E+00 | 9.2E+00 |
| 6.0E+00   | 9.9E-01            | 1.8E+00 | 4.0E+00 | 7.2E+00 | 1.1E+01 |
| 7.0E+00   | 1.1E+00            | 2.2E+00 | 4.8E+00 | 8.6E+00 | 1.3E+01 |
| 8.0E+00   | 1.3E+00            | 2.5E+00 | 5.6E+00 | 9.8E+00 | 1.5E+01 |
| 9.0E+00   | 1.4E+00            | 2.8E+00 | 6.2E+00 | 1.1E+01 | 1.6E+01 |
| 1.0E+01   | 1.5E+00            | 3.1E+00 | 6.8E+00 | 1.2E+01 | 1.7E+01 |

MASS AVERAGED DEPOSITION VELOCITIES FOR THE 1 TO 10 μm RANGE

| WIND SPEED u (m/s) |         |         |         |         |
|--------------------|---------|---------|---------|---------|
| 2.0                | 5.0     | 10.0    | 15.0    | 20.0    |
| 1.3E+00            | 2.6E+00 | 5.7E+00 | 1.0E+01 | 1.5E+01 |

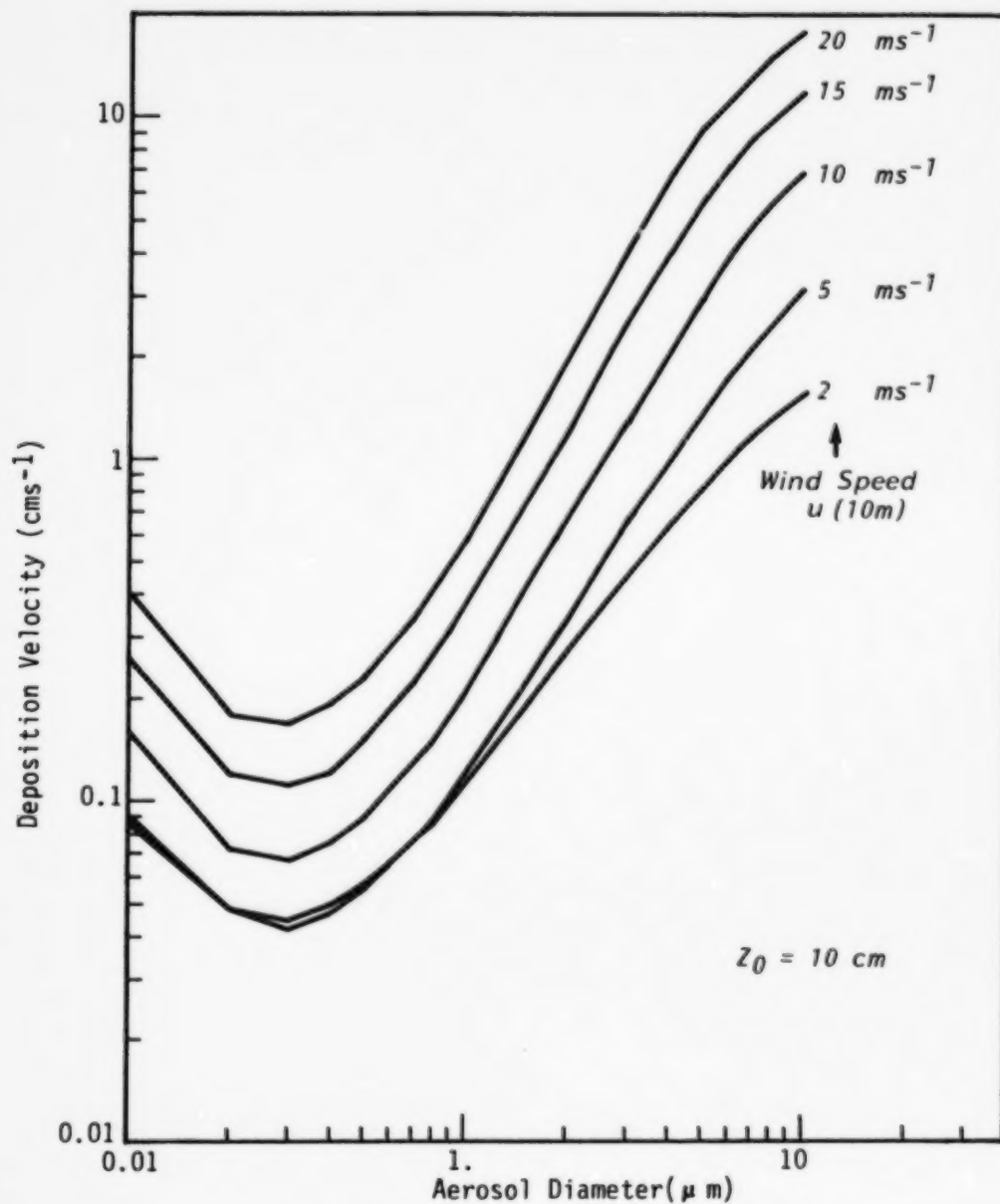


FIGURE 1  
AEROSOL DEPOSITION VELOCITIES FOR VARIOUS WIND  
SPEEDS AND AEROSOL DIAMETERS

together with

$$\begin{aligned} \text{Int} = & -6.6 - \exp \left\{ -378.051 + 16.498 \ln (0.148/D) \right. \\ & + \ln (3.156 \times 10^{-5} d^2 u_*^2) [-11.8178 - 0.28628 \ln \\ & (3.156 \times 10^{-5} d^2 u_*^2) + 0.32262 \ln (d/z_0) - 0.33850 \ln \\ & (D/z_0 u_*)] - 12.8044 \ln d \} \end{aligned} \quad (10)$$

$$Vt = 3.06 \times 10^2 d^2 \text{ cm/s} \quad (11)$$

$$\begin{aligned} D = & 2.43 \times 10^{-11} \left\{ 1 + 2.63 \times 10^{-6} [6.32 + 2.01 \exp \right. \\ & \left. (-8.32 \times 10^{-4} d)] \right\} \text{ cm}^2 \text{ s}^{-1} \end{aligned} \quad (12)$$

$$u_* = u (10m)/13 \quad (13)$$

$$z_0 = 10 \text{ cm}$$

The latter approach can be readily implemented in a computerized dispersion model.

#### 2.1.2 Particle Diameter 1 to 10 Micron Broad Size Distribution

Because of the strong dependence of  $V_g$  on  $d$ , the use of a  $V_g$  corresponding to the mass-mean diameter may introduce significant error. If possible, a mass weighted average over the size number distribution  $f(d)$  should be obtained, ie

$$\langle V_g \rangle = \int V_g (d) f (d) d^3 dd / \int f (d) d^3 dd \quad (14)$$

To illustrate this,  $\langle V_g \rangle$ 's were calculated for the "top hat" distribution,  $f = \text{constant}$  for  $1 < d < 10$  micron, zero elsewhere, and are shown in Table 1. These may be used in the absence of detailed information on the size distribution.

Note that mass or volume weighting (ie proportional to  $d^3$ ) is only appropriate if the radioactivity is distributed uniformly through the aerosol. If, for example, the radioactivity is distributed over the aerosol surface only, then a surface area weighted (ie  $d^2$ ) average should be used. Note also that large particles are responsible for most of the deposition flux.

## 2.2 Uncertainty Bounds - Deposition Velocity

Theory is not sophisticated enough to supply error estimates, consequently model uncertainty was estimated by comparing predicted  $V_g$ 's with experimental results. (See Appendix A). In most cases agreement appears to be within a factor of 3 (ie observed  $V_g$ 's fall approximately within an order of magnitude range centered on the predicted value).

Recommended upper and lower bounds for ( spatially and time-averaged)  $V_g$ 's are thus a factor of three higher or lower, respectively, than the predicted value. Exceptions may occur (1) for deposition to a forest canopy where  $V_g$ 's for sub-micron particles may approach the atmospheric turbulence transfer limited rates ( $V_g \sim 1$  to  $2$  cm/s for wind speeds of a few m/s) because of the high roughness and the large foliar surface area/12,13,14/ or (2) for deposition to very smooth surfaces, such as ice, where  $V_g$ 's may be very small for sub-micron aerosols. In the latter case representative  $V_g$ 's may be calculated from the equations given in Section 2.2 using an appropriate  $Z_0$  ( $\sim 10^{-2}$  to  $10^{-3}$  cm). (See Appendix A).

In the case of a polydisperse aerosol, preferential depletion of the aerosols in the fast depositing size ranges may lead to a change in the mass averaged deposition velocity as the plume ages. Table 1 indicates that this may significantly reduce deposition velocities.

## 3.0 WET DEPOSITION

The scavenging rate of aerosols of a given size may be theoretically calculated by integrating the efficiency, with which a hydrometeor of a given size collects the aerosols, multiplied by the volume swept out by a drop, per unit time, as it falls, over a drop size distribution/15/. Theoretical considerations suggest that the efficiency of collection is a strong function of aerosol size, with aerosols in the sub-micron range being inefficiently scavenged. Theoretical scavenging rates for polydisperse aerosols can therefore be derived from a mass weighted average of scavenging rates over the aerosol size distribution.

However, most of the available experimental data (which is limited) does not appear to show any strong dependence of aerosol collection efficiency and hence washout rate on aerosol diameter in the sub-micron range. (See Appendix B). This may occur for two reasons; (1) the mass averaged rate for polydispersed aerosols may tend to favour the larger values corresponding to the particles in the large end of the particle spectrum (collection efficiencies are expected to approach unity for diameters greater than a few microns), and (2) particles of diameter greater than ~0.1 micron will tend to grow rapidly by vapour condensation at RH~100%, with smaller particles tending to attach to cloud droplets/15/. These larger droplets are scavenged with an efficiency of order unity.

Slinn, in his recent review of wet deposition, also in "Atmospheric Sciences and Power Production"/15/ suggests the following approximation for the washout coefficient (fraction of plume material removed by rainfall per unit time).

$$\Lambda = \frac{0.5p E(R_m, d)}{R_m} s^{-1} \quad (15)$$

where  $R_m$  is the mass mean raindrop diameter (mm),  $p$  is the rainfall rate (mm/s) and  $E(R_m, d)$  is the collection efficiency of an aerosol of diameter  $d$  by a droplet of radius  $R_m$ .  $R_m$  can be related to  $p$  by

$$R_m = 0.35 \text{ mm} \left[ \frac{p(\text{mm/h})}{1 \text{ mm/h}} \right]^{0.75}$$

Based on the above discussion it seems reasonable to simplify (15) by assuming that  $E$  is not a strong function of  $d$ . Comparing available data, Slinn/15/ suggests that  $E \sim 0.3$  which gives

$$\Lambda = 1.2 \times 10^{-4} p^{0.75} s^{-1} \quad (16)$$

where  $p$  is now expressed in mm/h.

Equation (16) suggests that  $\Lambda$  depends on  $p^{0.75}$  which is in accord with available evidence which indicates that the power law dependence is between 0.5 and 1 (Appendix B).

### 3.1 Recommended Washout Coefficients

Equation (17) should be used to calculate the washout coefficient for all aerosol diameters. Equation (17) was obtained from equation (16) with the second significant figure dropped as unjustified, ie

$$\Lambda = 1 \times 10^{-4} p^{0.75} \quad s^{-1} \quad (17)$$

where the rainfall rate  $p$  is in mm/h.

### 3.2 Uncertainty Bounds - Washout Coefficients

Comparison with a variety of experimentally measured washout coefficients (see Appendix B) suggests that the above formula usually gives results accurate within a factor of 5. Reasonable upper and lower limits for the purposes of calculation of time and spatially averaged surface contamination should therefore be  $2 \times 10^{-5}$  and  $5 \times 10^{-4} s^{-1}$  for a rainfall rate of ~1mm/h. In this regard, note that local scavenging rates tend to show a very strong (order of magnitude or more) variation on a short time-scale basis/15/.

It is interesting to note that washout coefficients derived for HTO vapour for a near surface release (such as from a building) are also reasonably approximated by equation (17) as can be seen by comparison with Figure 2/16/.

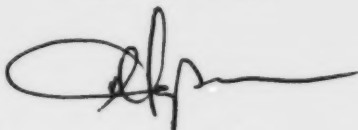
### 4.0 CONCLUDING REMARKS

Methods of parameterizing the dry and wet deposition rates of aerosols in the 0.2 to 10 micron diameter range were recommended in Sections 2.2 and 3.2 respectively. These parameters are based on physically sound principles, give reasonable agreement with (the limited amount of) available field data and appear to give the qualitatively correct dependence on important aerosol and environmental factors.

Recommended parameters should be viewed as giving suitable time and spatially averaged deposition rates at Ontario Hydro's NGS sites for the purpose of estimating surface contamination from a release of aerosols. The degree of uncertainty in recommended parameters was estimated by comparison with experimental data, leading to the conclusion that average deposition velocities may be accurate within a factor of three and washout coefficients within a factor of five. The possible variation in deposition rate as a function of location and time was also discussed briefly. These local and/or short time scale variations may be much larger (orders of magnitude). The discussion in the Appendices can be used for guidance in this case.

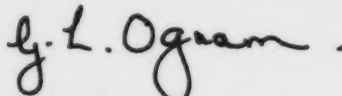
Note that the deposition models suggested are sophisticated enough to be readily adapted for use in more advanced atmospheric dispersion models, such as NEADM/17/.

Approved by:



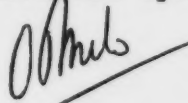
O.A. Kupcis  
Manager  
Chemical Research Department

Prepared by:



G.L. Ogram  
Research Scientist  
Atmospheric Research Section

Reviewed by:



O.T. Melo  
Supervising Engineer  
Atmospheric Research Section

GLO:msf:mf

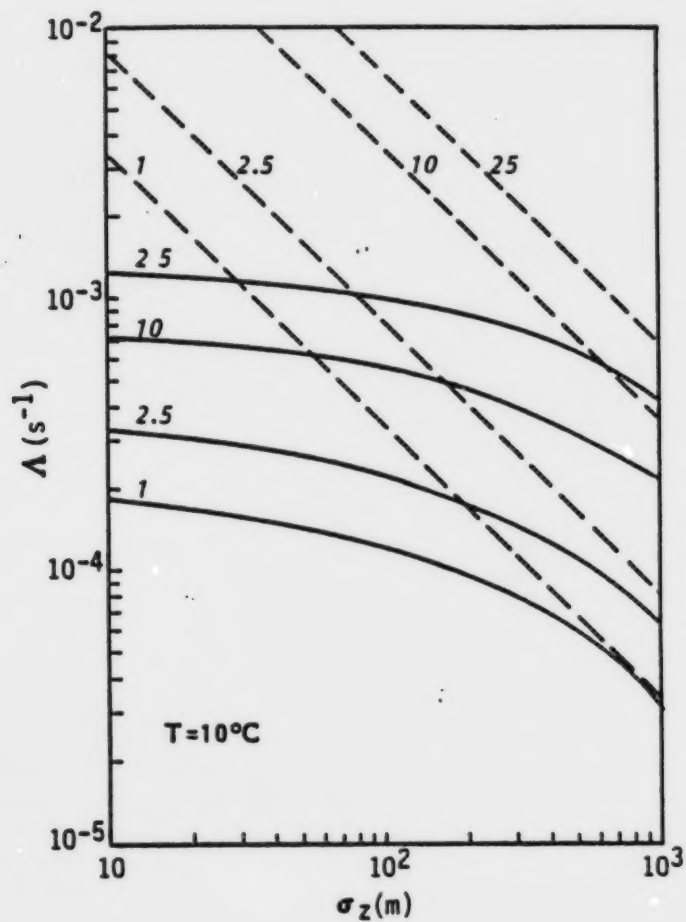


FIGURE 2  
EFFECTIVE HTO WASHOUT COEFFICIENT  
PLOTTED AGAINST PLUME VERTICAL  
STANDARD DEVIATION, FOR VARIOUS  
RAINFALL RATES ( $\text{mm h}^{-1}$ ) AT  $T=10^\circ\text{C}$ .  
THE DASHED LINES INDICATE THE  
CORRESPONDING EQUILIBRIUM WASH-  
OUT COEFFICIENTS.

## APPENDIX A

### UNCERTAINTY IN DEPOSITION VELOCITY

#### A.1 Comparison With Experiment

Much experimental information exists, however, as Sehmel/5/ puts it, "uncertainties abound". Information dating previous to 1980 is given in the reviews by Sehmel and others/4,5,18/. We briefly discuss these and some more recent results below. Only those results thought to be representative of conditions in the open environment, and where some characterisation of particle dimensions and surface and meteorological conditions exists, have been included.

- (1) Sehmel/4,5/ reviews a number of earlier wind tunnel and field experiments, and discusses in detail the complicated array of factors that may influence deposition. Sehmel quotes some of his own (unpublished) field results which agree well with his theory.
- (2) Garland/11/ presents new data for the deposition of mono-disperse particles to grass and compares these to other field and wind tunnel data (Figure A1). Assuming  $z_0 \sim 1$  cm (Table 1) and  $u \sim 30$  cm/s/11/,  $V_g$  values were calculated using the theory of Section 2 and were also plotted in Figure A1 where they appear to give good agreement, given the scatter within the results.

Experimental evidence was also given that growth of hygroscopic submicron particles, by vapour absorption, in the interfacial layer near the surface where RH is high, is not rapid enough to enhance  $V_g$ 's by more than a factor of 2.

- (3) Hofhen et al/13/ measured trace element concentrations in various aerosol size ranges between 0.3 and 3 micron mass mean diameter at various heights within forest canopies (beech and spruce) from which they inferred fluxes using mass balance considerations.  $V_g$ 's exhibited a minimum at about  $d = 1$  micron, but only varied between about 0.5 and 3 cm/s for all diameters. This supports the contention that sub-micron aerosol deposition velocities to forest tend to approach atmospheric transfer limited values.
- (4) Jonas and Heinemann/14/, using both monodisperse and polydisperse radioactive tracer aerosols, measured

Figure A1  
(after Garland /11/)

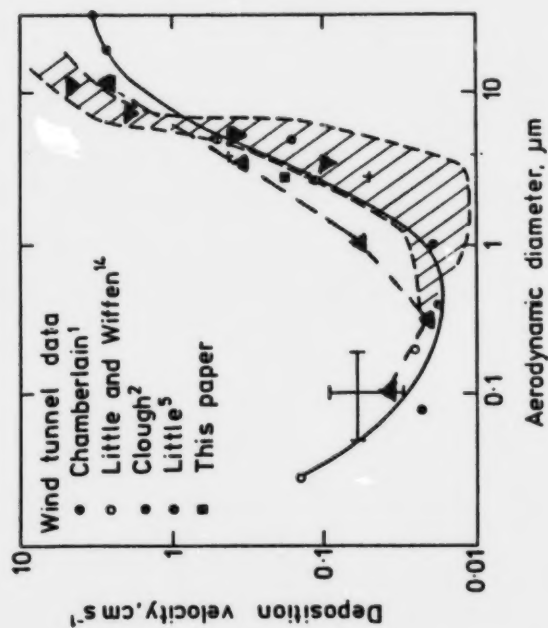


Fig. 1. Deposition velocity of particles to grass.  
Solid Curve: wind tunnel results for  $u_* = 35 \text{ cm s}^{-1}$ .  
Crosses: field data presented here.  
Hatched area: field data of Jonas and Vogt<sup>23</sup>.

Triangles: values calculated from Sehmel's model,  $Z_0 = 1 \text{ cm}$ ,  $u_* = 30 \text{ cm/s}$ .  
Inverted triangles: Measurements of Jonas and Heinemann /14/.

deposition velocities to various surface types by the direct method of comparing time integrated air concentrations to total deposited material per unit area. Measured  $V_g$ 's to grass have been added to Figure A1, and also appear to agree reasonably well with the predictions of Sehmel's model (certainly within a factor of three). They observe a stronger dependence of  $V_g$  on  $d$  than predicted by the model. They also find that deposition to bare, plane surfaces is lower than that to grass by a factor of 2 to 4 and that  $V_g$ 's to forests may be an order of magnitude higher (~1 cm/s for particles of a few micron diameter).

It is noted for completeness that, at present, there is a good deal of controversy in regard to measured  $V_g$ 's for the sulphate aerosols of interest in the acid rain problem. We sidestep this question by noting that the high  $V_g$  values ( $> 0.1$  cm/s) obtained for sub-micron aerosols by eddy correlation methods are in conflict with values inferred from direct measurements of air and surface deposited concentrations for well characterised particles. The latter are probably more representative for the present case. We have therefore restricted ourselves mainly to consideration of the results from controlled releases and to chemically less complicated systems than aerosol sulphate.

## A.2 Uncertainty In Input

The sensitivity of the recommended dry deposition model (Section 2) to input data was briefly examined in order to (1) get an idea of potential variation in predicted  $V_g$ 's and (2) justify the simplifying assumptions of Section 2.0.

### Roughness Length $Z_0$

A representative value of 10 cm was chosen. Spatially averaged  $Z_0$  values for the terrain surrounding Hydro's NGS sites may reasonably range between about 1 and 40 cm (Table 1). Tables A1 and A2 show  $V_g$ 's calculated using these  $Z_0$  values. Results show that  $V_g$  increases with  $Z_0$ , by a maximum factor of ~4.5 for low wind speeds and small  $d$ , and by  $<10\%$  for high winds and large  $d$ . Note that, strictly speaking, Sehmel's correlation was derived only for  $Z_0 < 10$  cm. As seen earlier, evidence exists that  $V_g$ 's for very rough surfaces with high effective collection areas (eg forest canopies) can approach 1 cm/s for sub-micron particles.

$V_g$ 's were also calculated for very smooth surfaces (eg ice) where  $Z_0 \sim 0.01$  to  $0.001$  cm (Table 1). Results are shown in

Tables A3 and A4. Note that  $V_g$ 's in the sub-micron range can be much smaller than for  $Z_0$  values of a few cm.

#### Monin-Obukhov Length L

$V_g$ 's were not calculated for different L as Sehmel/2,3,5/ has already shown the results to be relatively insensitive to atmospheric stability.

#### Friction Velocity $u_*$

We related  $u_*$  to the measured wind speed at 10m,  $u(10m)$ , by using the logarithmic profile for a neutral atmosphere. The ratio  $u/u_*$  can be corrected for stability by writing it

$$u/u_* = 2.86 (\ln(Z/Z_0) + \psi(Z/L))$$

Using the expressions given by Businger/10/ for  $\psi(Z/L)$  we obtain  $u/u_* = 26$  for a very stable atmosphere ( $L=10m$ ),

$u/u_* = 13$  for a near neutral atmosphere ( $L \rightarrow \infty$ ) and  $u/u_* = 11$

for an unstable atmosphere ( $L = -10m$ ), for  $Z_0 = 10$  cm. That is, inferred values of  $u_*$  may be overestimated by a factor of two

under highly stable conditions (which only occur for very low wind speeds). In this worst case, Table A5 shows that inferred  $V_g$ 's differ by less than a factor of two from the values recommended in Section 2. Note also that, contrary to what one might expect, for low wind speeds, the model gives increasing  $V_g$ 's with decreasing  $u$  for  $u < 20$  to 30 cm/s. Sehmel/5/

comments that it is uncertain whether this apparent minimum  $V_g$  for  $u$  in the range 20 to 30 cm/s "is physically real or reflects uncertainties in the prediction techniques".

Table A1

PARTICLE DEPOSITION VELOCITIES (cm/s) FOR VARIOUS WIND SPEEDS  
AND PARTICLE DIAMETERS (NEUTRAL ATMOSPHERE INT1-2 = -11.1)

ROUGHNESS LENGTH  $Z_0 = 1$  cm  
PARTICLE DENSITY =  $1$  g/cm<sup>3</sup>

| DIAM ( $\mu$ m) | WIND SPEED $u$ (m/s) |         |         |         |         |
|-----------------|----------------------|---------|---------|---------|---------|
|                 | 2.0                  | 5.0     | 10.0    | 15.0    | 20.0    |
| 1.0E-01         | 3.2E-02              | 3.5E-02 | 6.3E-02 | 1.1E-01 | 1.8E-01 |
| 2.0E-01         | 1.9E-02              | 1.9E-02 | 3.1E-02 | 5.2E-02 | 8.3E-02 |
| 3.0E-01         | 1.8E-02              | 1.8E-02 | 3.0E-02 | 4.9E-02 | 7.8E-02 |
| 4.0E-01         | 2.0E-02              | 2.0E-02 | 3.4E-02 | 5.7E-02 | 8.9E-02 |
| 5.0E-01         | 2.3E-02              | 2.4E-02 | 4.1E-02 | 6.9E-02 | 1.1E-01 |
| 6.0E-01         | 2.7E-02              | 2.9E-02 | 5.0E-02 | 8.5E-02 | 1.4E-01 |
| 7.0E-01         | 3.2E-02              | 3.4E-02 | 6.1E-02 | 1.0E-01 | 1.7E-01 |
| 8.0E-01         | 3.7E-02              | 4.1E-02 | 7.3E-02 | 1.3E-01 | 2.1E-01 |
| 9.0E-01         | 4.3E-02              | 4.8E-02 | 8.8E-02 | 1.5E-01 | 2.5E-01 |
| 1.0E+00         | 4.9E-02              | 5.6E-02 | 1.0E-01 | 1.8E-01 | 3.0E-01 |
| 2.0E+00         | 1.3E-01              | 1.7E-01 | 3.5E-01 | 6.4E-01 | 1.1E+00 |
| 3.0E+00         | 2.3E-01              | 3.4E-01 | 7.3E-01 | 1.4E+00 | 2.3E+00 |
| 4.0E+00         | 3.4E-01              | 5.5E-01 | 1.2E+00 | 2.3E+00 | 3.8E+00 |
| 5.0E+00         | 4.4E-01              | 7.7E-01 | 1.7E+00 | 3.3E+00 | 5.3E+00 |
| 6.0E+00         | 5.5E-01              | 1.0E+00 | 2.3E+00 | 4.2E+00 | 6.7E+00 |
| 7.0E+00         | 6.5E-01              | 1.2E+00 | 2.8E+00 | 5.0E+00 | 7.9E+00 |
| 8.0E+00         | 7.4E-01              | 1.4E+00 | 3.2E+00 | 5.8E+00 | 8.9E+00 |
| 9.0E+00         | 8.3E-01              | 1.6E+00 | 3.7E+00 | 6.4E+00 | 9.7E+00 |
| 1.0E+01         | 9.2E-01              | 1.8E+00 | 4.0E+00 | 7.0E+00 | 1.0E+01 |

MASS AVERAGED DEPOSITION VELOCITIES FOR THE 1 TO 10  $\mu$ m RANGE

| WIND SPEED $u$ (m/s) |         |         |         |         |      |
|----------------------|---------|---------|---------|---------|------|
|                      | 2.0     | 5.0     | 10.0    | 15.0    | 20.0 |
| 7.7E-01              | 1.5E+00 | 3.3E+00 | 5.9E+00 | 8.9E+00 |      |

Table A2

PARTICLE DEPOSITION VELOCITIES (cm/s) FOR VARIOUS WIND SPEEDS  
AND PARTICLE DIAMETERS (NEUTRAL ATMOSPHERE INT1-2 = -3.5)

ROUGHNESS LENGTH  $Z_0 = 40$  cm  
PARTICLE DENSITY =  $1$  g/cm<sup>3</sup>

| DIAM ( $\mu$ m) | WIND SPEED $\mu$ (m/s) |         |         |         |         |
|-----------------|------------------------|---------|---------|---------|---------|
|                 | 2.0                    | 5.0     | 10.0    | 15.0    | 20.0    |
| 1.0E-01         | 1.6E-01                | 1.6E-01 | 2.7E-01 | 4.4E-01 | 6.9E-01 |
| 2.0E-01         | 8.7E-02                | 7.9E-02 | 1.2E-01 | 2.0E-01 | 3.0E-01 |
| 3.0E-01         | 7.9E-02                | 7.1E-02 | 1.1E-01 | 1.8E-01 | 2.7E-01 |
| 4.0E-01         | 8.5E-02                | 7.8E-02 | 1.2E-01 | 1.9E-01 | 3.0E-01 |
| 5.0E-01         | 9.6E-02                | 9.0E-02 | 1.4E-01 | 2.3E-01 | 3.5E-01 |
| 6.0E-01         | 1.1E-01                | 1.1E-01 | 1.7E-01 | 2.8E-01 | 4.3E-01 |
| 7.0E-01         | 1.3E-01                | 1.2E-01 | 2.0E-01 | 3.3E-01 | 5.2E-01 |
| 8.0E-01         | 1.4E-01                | 1.5E-01 | 2.4E-01 | 4.0E-01 | 6.3E-01 |
| 9.0E-01         | 1.6E-01                | 1.7E-01 | 2.9E-01 | 4.8E-01 | 7.5E-01 |
| 1.0E+00         | 1.8E-01                | 1.9E-01 | 3.3E-01 | 5.6E-01 | 8.9E-01 |
| 2.0E+00         | 4.4E-01                | 5.5E-01 | 1.0E+00 | 1.8E+00 | 3.0E+00 |
| 3.0E+00         | 7.4E-01                | 1.0E+00 | 2.1E+00 | 3.8E+00 | 6.3E+00 |
| 4.0E+00         | 1.0E+00                | 1.6E+00 | 3.4E+00 | 6.2E+00 | 1.0E+01 |
| 5.0E+00         | 1.3E+00                | 2.2E+00 | 4.8E+00 | 8.8E+00 | 1.4E+01 |
| 6.0E+00         | 1.6E+00                | 2.8E+00 | 6.2E+00 | 1.1E+01 | 1.8E+01 |
| 7.0E+00         | 1.9E+00                | 3.4E+00 | 7.6E+00 | 1.4E+01 | 2.2E+01 |
| 8.0E+00         | 2.1E+00                | 4.0E+00 | 8.9E+00 | 1.6E+01 | 2.5E+01 |
| 9.0E+00         | 2.3E+00                | 4.5E+00 | 1.0E+01 | 1.8E+01 | 2.7E+01 |
| 1.0E+01         | 2.5E+00                | 5.0E+00 | 1.1E+01 | 1.9E+01 | 2.9E+01 |

MASS AVERAGED DEPOSITION VELOCITIES FOR THE 1 TO 10  $\mu$ m RANGE

| WIND SPEED $u$ (m/s) |         |         |         |         |  |
|----------------------|---------|---------|---------|---------|--|
| 2.0                  | 5.0     | 10.0    | 15.0    | 20.0    |  |
| 2.1E+00              | 4.1E+00 | 9.2E+00 | 1.6E+01 | 2.5E+01 |  |

Table A3

PARTICLE DEPOSITION VELOCITIES (cm/s) FOR VARIOUS WIND SPEEDS  
AND PARTICLE DIAMETERS (NEUTRAL ATMOSPHERE INT1-2 = -13.2)

ROUGHNESS LENGTH  $Z_0 = 1E-2$  cm  
PARTICLE DENSITY = 1 g/cm<sup>3</sup>

| DIAM ( $\mu$ m) | WIND SPEED u (m/s) |         |         |                 |
|-----------------|--------------------|---------|---------|-----------------|
|                 | 2.0                | 5.0     | 10.0    | 15.0 20.0       |
| 1.0E-01         | 4.3E-03            | 5.3E-03 | 1.0E-02 | 1.9E-02 3.3E-02 |
| 2.0E-01         | 2.7E-03            | 3.1E-03 | 5.8E-03 | 1.0E-02 1.7E-02 |
| 3.0E-01         | 2.8E-03            | 3.2E-03 | 5.8E-03 | 1.0E-02 1.7E-02 |
| 4.0E-01         | 3.4E-03            | 3.9E-03 | 7.0E-03 | 1.2E-02 2.0E-02 |
| 5.0E-01         | 4.2E-03            | 4.8E-03 | 8.8E-03 | 1.6E-02 2.6E-02 |
| 6.0E-01         | 5.1E-03            | 6.0E-03 | 1.1E-02 | 2.0E-02 3.3E-02 |
| 7.0E-01         | 6.2E-03            | 7.5E-03 | 1.4E-02 | 2.5E-02 4.1E-02 |
| 8.0E-01         | 7.5E-03            | 9.1E-03 | 1.7E-02 | 3.1E-02 5.2E-02 |
| 9.0E-01         | 8.9E-03            | 1.1E-02 | 2.1E-02 | 3.8E-02 6.4E-02 |
| 1.0E+00         | 1.0E-02            | 1.3E-02 | 2.5E-02 | 4.6E-02 7.8E-02 |
| 2.0E+00         | 3.3E-02            | 4.6E-02 | 9.7E-02 | 1.9E-01 3.3E-01 |
| 3.0E+00         | 6.7E-02            | 1.0E-01 | 2.2E-01 | 4.4E-01 7.9E-01 |
| 4.0E+00         | 1.1E-01            | 1.7E-01 | 4.0E-01 | 8.1E-01 1.5E+00 |
| 5.0E+00         | 1.6E-01            | 2.7E-01 | 6.3E-01 | 1.3E+00 2.3E+00 |
| 6.0E+00         | 2.2E-01            | 3.7E-01 | 8.9E-01 | 1.8E+00 3.2E+00 |
| 7.0E+00         | 2.8E-01            | 4.8E-01 | 1.2E+00 | 2.3E+00 4.1E+00 |
| 8.0E+00         | 3.4E-01            | 6.1E-01 | 1.5E+00 | 2.9E+00 4.9E+00 |
| 9.0E+00         | 4.1E-01            | 7.3E-01 | 1.8E+00 | 3.4E+00 5.7E+00 |
| 1.0E+01         | 4.9E-01            | 8.7E-01 | 2.1E+00 | 4.0E+00 6.4E+00 |

MASS AVERAGED DEPOSITION VELOCITIES FOR THE 1 TO 10  $\mu$ m RANGE

| WIND SPEED u (m/s) |         |         |                 |
|--------------------|---------|---------|-----------------|
| 2.0                | 5.0     | 10.0    | 15.0 20.0       |
| 3.8E-01            | 6.6E-01 | 1.6E+00 | 3.1E+00 5.2E+00 |

Table A4

PARTICLE DEPOSITION VELOCITIES (cm/s) FOR VARIOUS WIND SPEEDS  
AND PARTICLE DIAMETERS (NEUTRAL ATMOSPHERE INT1-2 = -13.2)

ROUGHNESS LENGTH  $Z_0 = 1E-3$  cm  
PARTICLE DENSITY = 1 g/cm<sup>3</sup>

| DIAM ( $\mu$ m) | WIND SPEED u (m/s) |         |         |                 |
|-----------------|--------------------|---------|---------|-----------------|
|                 | 2.0                | 5.0     | 10.0    | 15.0 20.0       |
| 1.0E-01         | 1.6E-03            | 2.1E-03 | 4.3E-03 | 8.1E-03 1.4E-02 |
| 2.0E-01         | 1.1E-03            | 1.3E-03 | 2.5E-03 | 4.5E-03 7.5E-03 |
| 3.0E-01         | 1.2E-03            | 1.4E-03 | 2.6E-03 | 4.7E-03 7.8E-03 |
| 4.0E-01         | 1.5E-03            | 1.8E-03 | 3.3E-03 | 5.6E-03 9.7E-03 |
| 5.0E-01         | 1.9E-03            | 2.3E-03 | 4.3E-03 | 7.5E-03 1.3E-02 |
| 6.0E-01         | 2.5E-03            | 3.0E-03 | 5.5E-03 | 9.7E-03 1.6E-02 |
| 7.0E-01         | 3.1E-03            | 3.8E-03 | 7.0E-03 | 1.2E-02 2.1E-02 |
| 8.0E-01         | 3.8E-03            | 4.7E-03 | 8.7E-03 | 1.6E-02 2.6E-02 |
| 9.0E-01         | 4.6E-03            | 5.8E-03 | 1.1E-02 | 1.9E-02 3.3E-02 |
| 1.0E+00         | 5.5E-03            | 6.9E-03 | 1.3E-02 | 2.4E-02 4.0E-02 |
| 2.0E+00         | 1.9E-02            | 2.6E-02 | 5.2E-02 | 1.0E-01 1.8E-01 |
| 3.0E+00         | 4.1E-02            | 5.8E-02 | 1.3E-01 | 2.5E-01 4.5E-01 |
| 4.0E+00         | 7.0E-02            | 1.0E-01 | 2.3E-01 | 4.7E-01 8.7E-01 |
| 5.0E+00         | 1.1E-01            | 1.6E-01 | 3.7E-01 | 7.7E-01 1.4E+00 |
| 6.0E+00         | 1.5E-01            | 2.3E-01 | 5.4E-01 | 1.1E+00 2.1E+00 |
| 7.0E+00         | 2.0E-01            | 3.1E-01 | 7.4E-01 | 1.5E+00 2.6E+00 |
| 8.0E+00         | 2.5E-01            | 4.0E-01 | 9.5E-01 | 2.0E+00 3.5E+00 |
| 9.0E+00         | 3.1E-01            | 4.9E-01 | 1.2E+00 | 2.4E+00 4.3E+00 |
| 1.0E+01         | 3.7E-01            | 6.0E-01 | 1.4E+00 | 2.9E+00 5.0E+00 |

MASS AVERAGED DEPOSITION VELOCITIES FOR THE 1 TO 10  $\mu$ m RANGE

| WIND SPEED u (m/s) |         |         |                 |
|--------------------|---------|---------|-----------------|
| 2.0                | 5.0     | 10.0    | 15.0 20.0       |
| 2.8E-01            | 4.5E-01 | 1.1E+00 | 2.2E+00 3.8E+00 |

Table A5

DEPENDENCE OF PARTICLE DEPOSITION VELOCITIES (cm/s) ON RATIO OF  
WIND SPEED TO FRICTION VELOCITY (13 FOR A NEUTRAL ATMOSPHERE, 26  
FOR A STABLE ATMOSPHERE, RESPECTIVELY)

ROUGHNESS LENGTH = 10 cm  
PARTICLE DENSITY = 1gm/cm<sup>3</sup>  
WIND SPEED AT 10m = 2 m/s

|           | NEUTRAL | STABLE  |
|-----------|---------|---------|
| DIAM (μm) |         |         |
| 1.0E-01   | 8.8E-02 | 1.4E-01 |
| 2.0E-01   | 4.9E-02 | 8.2E-02 |
| 3.0E-01   | 4.5E-02 | 7.6E-02 |
| 4.0E-01   | 4.9E-02 | 8.2E-02 |
| 5.0E-01   | 5.6E-02 | 9.1E-02 |
| 6.0E-01   | 6.5E-02 | 1.0E-01 |
| 7.0E-01   | 7.5E-02 | 1.2E-01 |
| 8.0E-01   | 8.6E-02 | 1.3E-01 |
| 9.0E-01   | 9.8E-02 | 1.5E-01 |
| 1.0E+00   | 1.1E-01 | 1.6E-01 |
| 2.0E+00   | 2.7E-01 | 3.2E-01 |
| 3.0E+00   | 4.6E-01 | 4.7E-01 |
| 4.0E+00   | 6.5E-01 | 5.9E-01 |
| 5.0E+00   | 8.3E-01 | 6.9E-01 |
| 6.0E+00   | 9.9E-01 | 7.7E-01 |
| 7.0E+00   | 1.1E+00 | 8.5E-01 |
| 8.0E+00   | 1.3E+00 | 9.1E-01 |
| 9.0E+00   | 1.4E+00 | 9.8E-01 |
| 1.0E+01   | 1.5E+00 | 1.0E+00 |

## APPENDIX B

### UNCERTAINTY IN WASHOUT COEFFICIENT

#### B.1 Comparison With Experiment

Slinn, in his comprehensive review/15/, describes the results of a number of experiments. We will not discuss these in detail here except to note that, (1) carefully controlled experimental results are very limited, and (2) these results are, in general, within a factor of 5 of the predictions of the values suggested in Section 3.

Some of the available results are shown in Figures B1, B2 and B3. B1 and B2 show reasonable agreement between measured washout coefficients and the absolute values and rainfall rate dependences predicted by equation (17), Section 3. Figure B3 shows measured and theoretical raindrop collection efficiencies for aerosols of various diameters. The figure shows (1) that collection efficiencies for sub-micron particles are much greater than expected from theoretical considerations if growth by condensation is ignored, and (2) that a representative collection efficiency of  $\sim 0.3$ , as assumed in Section 3, appears reasonable.

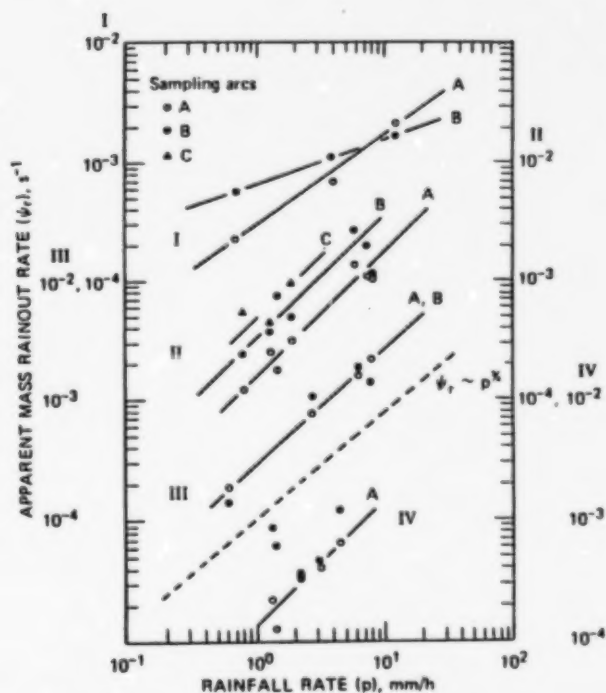


Fig. 11.16 The apparent rain scavenging rate for aerosol particles measured by Dana and Wolf (1968), Wolf and Dana (1969), Dana, Wolf, and du Plessis (1970), and Dana (1971, 1972). All tests were during fairly steady (prefrontal) rain. Sampling arcs A, B, and C were located 50, 100, and 150 ft downwind from a 26-ft tower. Curves I: rhodamine particles, mass median diameter (mmd) =  $11.2 \mu m$ . Curves II: fluorescein particles, mean  $\alpha^2 \rho_p = 35 \mu m^2 \cdot g/cm^3$ . Curves III: rhodamine particles, mmd =  $1.2 \mu m$ . Curve IV: rhodamine particles, mmd =  $4.8 \mu m$ . Different depositions on different arcs suggest the presence of simultaneous dry deposition; the polydispersity of the aerosol size distribution may explain why the removal rates are substantially greater than the rates that would be predicted on the basis of the particle/drop collision efficiency given in Fig. 11.5. [From W. G. N. Slinn, Some Approximations for the Wet and Dry Removal of Particles and Gases from the Atmosphere, *J. Water, Air, Soil Poll.*, 7: 513-543 (1977).]

Figure B1  
(from /15/)

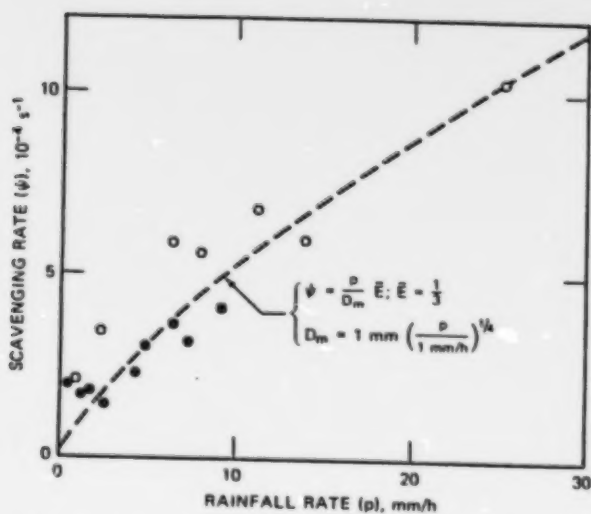


Fig. 11.36 A comparison of the theoretical prediction of Eq. 11.32 (dashed curve) against experimental data obtained by Burtsev, Burtseva, and Malakov (1970) for the in-cloud scavenging of tracer mass released into the top of the rain shaft (●) and into the region of "cloud drops" (○) of a cumulonimbus cloud. [Based on W. G. N. Slinn, Some Approximations for the Wet and Dry Removal of Particles and Gases from the Atmosphere, *J. Water, Air, Soil Poll.*, 7: 513-543 (1977).]

Figure B2  
(from /15/)

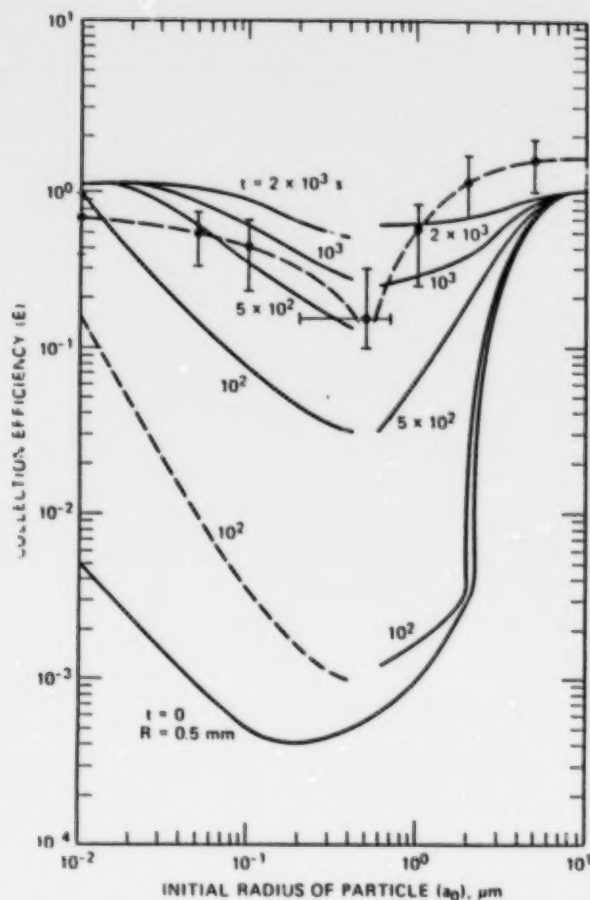


Fig. 11.35 An interpretation of the measured collection efficiency of Radke, Eltgroth, and Hobbs (1978) as a function of particle size. The data curve shows the mean ( $\bullet$ ) and standard deviation about the mean ( $\pm$ ) for eight sets of data collected over a 3-yr period. The solid curve at the bottom of the figure (labeled  $t = 0$ ) is the collection efficiency from Fig. 11.5 for mean raindrop radius  $R = 0.5$  mm. The dashed curve labeled  $t = 10^3$  (s) is obtained assuming  $E = E(0) \exp(-\alpha t) + 1.0 [1 - \exp(-\alpha t)]$  with the attachment rate,  $\alpha$ , for Brownian coagulation with  $10^5$  droplets/cm<sup>3</sup> of radius  $r = 10$   $\mu$ m. The solid curves at  $a < 0.5$   $\mu$ m labeled  $10^2$ ,  $5 \times 10^2$ ,  $10^3$ , and  $2 \times 10^3$  s are obtained by using the attachment rate labeled as curve c in Fig. 11.30. The solid curves at  $a > 0.5$   $\mu$ m are obtained by assuming that the particles grew by water vapor condensation to the size (and correspondingly increased collection efficiency) given by  $a(t) = [a_0^2 + (t \mu^3/100 s)]^{1/2}$ .

Figure B3  
(from /15/)

## APPENDIX C

### COMMENT ON PAST APPROACHES AND FUTURE IMPROVEMENTS IN MODELLING DEPOSITION PARAMETERS

It has been common to use a single value of  $V_g$  or  $\Lambda$  to describe aerosol deposition. This appears to be no longer justified as we know that these parameters can depend strongly on factors such as aerosol diameter, wind speed, surface conditions, rainfall rate, etc. If these dependences are not taken into account unnecessary errors of an order or magnitude or more may be introduced.

So called "conservative" calculations have also been made by specifying upper and lower bounds to the deposition parameter and using the lower value to calculate depletion and higher value to calculate deposition. In the author's opinion such an approach makes little sense, as it violates conservation of mass. In other words, one may obtain total deposited amounts that exceed the amount emitted. Rapid deposition requires, of necessity, rapid plume depletion! The present approach of taking a representative deposition parameter, with reasonable uncertainty bounds, is therefore preferable as a means of estimating the potential uncertainty in surface contamination and plume travel distance.

In future, the dry deposition model recommended here, can be extended to deal with the effects of atmospheric stability, if the Monin-Obukhov length,  $L$ , is available. From the discussion in Appendix A, it appears that the effect is small in regard to deposition velocities referred to a 1 m reference height. However, if more sophisticated surface depletion models are used, where the effect of deposition on the plume profile is accounted for, then the effect of stability may become more important/19/.

Surface effects are certainly likely to be more complex than implied by a simple dependence on roughness length. Methods of describing the dependence, on, eg, the type and density of vegetation are not well established. In addition, little appears to be known about deposition to buildings.

Little quantitative information exists regarding aerosol scavenging by snow. Slinn/15/ presents some data for inorganic iodine and silver iodide which indicated "snowout coefficients" between  $3 \times 10^{-5}$  and  $1 \times 10^{-4} \text{ s}^{-1}$  in the former case and  $3 \times 10^{-7}$  and  $2 \times 10^{-5} \text{ s}^{-1}$  in the latter case, with a linear dependence on equivalent rainfall rate.

## REFERENCES

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